RISK ANALYSIS FOR AMMUNITION STORAGE IN THEATRES-OF-OPERATION

by

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For many elements of the Army, it is necessary to temporarily store quantities of ammunition and other explosives in order to perform their mission in a combat theatre. It is possible that, for tactical or other reasons, a commander in a combat area may make an on-the-spot decision to deviate from normal DOD safety standards. Although the safety standards provide reduced Quantity-Distances (QD) for storage in theatres of operations, the added risks to personnel and assets created by such reductions are not specified. This paper details the results of a theoretical study to provide field commanders with the tools to make a more informed decision when weighing safety against operational advantage. Specific guidelines are given that describe in tangible, quantitative terms, the increased risk incurred by specific deviations from the QD values recommended for permanent storage for ammunition.

PROBLEM DEFINITION

A risk analysis is basically a study to determine the probability that something bad will happen in a given set of circumstances. In a situation involving a violation (or even a non-violation) of QD standards for ammunition storage safety, the final risk factor will usually be an accumulation of the probabilities of subcomponent happenings. In the simplest case, there are two probabilities involved; the probability of an event (such as an accidental explosion), and the probability of an effect (such as someone being killed by a piece of explosion debris). The present QD standards are limiting values which have been judged to keep these probabilities, and the resulting risk factor, within acceptable limits. If a field commander decides to establish an ammunition holding area (AHA) at a distance less than the specified QD from a route of heavy military traffic (equivalent to a "peacetime" public traffic route), his decision does not change the probability that the AHA will accidently explode, but it <u>does</u> increase the probability that a soldier in a vehicle will be struck by a piece of debris from the explosion. Therefore his decision will increase the risk to personnel.

In reality, it is very difficult to assign an absolute value to the risk factor resulting from the commander's violation of the QD. This is due to the fact that, while the probabilities of some events/effects can be quantified by tests and statistical data, the probabilities of others will remain obscure. For example, we can predict the probability of a critical level of airblast pressure (from a given explosion) very accurately, and the probability of an impact by a piece of debris of specified size with reasonable accuracy, based on data from explosive tests. On the other hand, we have only a fuzzy idea of the probability that an explosive accident will occur in a given situation.

Fortunately, the problem of predicting the probability of an accidental explosion is, in a sense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1994**	2. REPORT TYPE	3. DATES COVERED **00-00-1994 to 00-00-1994**

4. TITLE AND SUBTITLE **Risk Analysis for Ammunition Storage in Theaters-of-Operation**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Waterways Experiment Station,3909 Halls Ferry Road,Vicksburg,MS,39180-6199**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM000767. Proceedings of the Twenty-Sixth DoD Explosives Safety Seminar Held in Miami, FL on 16-18 August 1994.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**22**	

academic. We can safely assume that the probability of an initial, accidental explosion will not change, whether the standard QD values are observed or not. This means we can assume a fixed probability of an accident occurring, and evaluate only the additional risk created by violation of the QD's. The resulting guidelines will then tell a commander that a given QD violation will increase the risk of personnel injury, for example, by a factor of 50 percent, or a factor of two, or four, etc.

EXPLOSION HAZARDS OF INTEREST

Recent tests (Camp Stanley simulations, (Joachim, 1992)) indicate that airblast is probably not a direct factor in sympathetic detonation of individual ammo stacks. Airblast can, however, cause injury to personnel. Fortunately, blast pressure levels at which bodily injury occurs are well documented. And given the Net Explosive Quantity (NEQ), which for our purposes we assume to be the worst case - the mass detonation of an entire ammo stack - we can read peak pressures and durations from existing airblast curves. With this in mind, fragment hazard will be the main topic of concern in this paper.

The fragment hazard problem may be described by the example shown in Figure 1. Item A is an ammo stack, and item B is a second ammo stack located some distance from A. In a combat situation, the ammo stacks would most likely be uploaded trucks, or ammunition stacked on the ground. Let us assume that an accidental explosion occurs at A, the primary source. B is an adjacent unit that is sympathetically detonated by the detonation of the primary source. Thus, given an explosion at A, P_A is the probability that a target T is hit by a fragment from the explosion at A. Given an explosion at B, P_B is the probability of a hit on target T by a fragment from the explosion at B. $P_{B|A}$ is the probability that an explosion at A causes B to sympathetically detonate. The problem of compounded probabilities is simplified by the fact that, although the detonation of B is dependent on the detonation of A, the effects (particularly the fragmentation effects that are the main focus of this study) may be considered as independent events. Statistically, this means that the probability of hit for each event can be determined independently and then combined.

The solution to the problem is based on a "favorable outcome" which in this case is the probability of not getting hit, or survival. Survival for A is expressed as $P_{SA} = 1 - P_A$, and for B as $P_{SB} = 1 - P_B$. For the simple case where both A and B explode, the probability of a "hit" at T is expressed as:

$$P_T = 1 - P_S(A\&B) = 1 - (1 - P_A) * (1 - P_B) \tag{1}$$

Notice that $P_T = 0$ when P_A and $P_B = 0$, and $P_T = 1$ when P_A and $P_B = 1$. $P_T = 0.75$ when P_A and $P_B = 0.5$.

$$P_T = 1 - (1 - P_A) * (1 - P_{B|A})$$

In the above example, it was assumed that B exploded (A always explodes). Now consider the conditional probability $P_{B|A}$ (that B will explode, given an explosion at A). Here the "favorable outcome" is a hit by A at B, and the conditional probability, if P_A is not 0, may be expressed as $P_A * P_{B|A}$ (Miller and Freund 1977). Thus:

Given these relationships, all that remains is to determine the individual probabilities. Unfortunately, this is not an easy task. One problem area we have is accurately predicting the probabilty of a secondary, sympathetic explosion. If the commander violates (reduces) the QD standard for separation of uploaded ammunition trucks by 50 percent, we can predict the probability that high-energy fragments will impact ammunition on an adjacent truck, introducing the possibility of a secondary

detonation. But we don't have a handle on the factors (mass, velocity, angle of impact, etc.) that cause a sympathetic detonation of one or more munitions in a second stack, or that the detonation of one munition will lead to a mass detonation of the entire stack. Such uncertainties for the time being, must be addressed by assuming the worst case - i.e., mass detonation of secondary stacks that violate peacetime safety standards.

APPROACH

The lack of sufficient fragment hazard data dictated that the problem be approached analytically. The most suitable tool for this analysis was determined to be the QD Fragment Hazard (FRAGHAZ) Computer Program (McClesky, 1988), developed for the Defense Explosives Safety Board (DDESB) by the U.S. Naval Surface Warfare Center (NSWC).

FRAGHAZ provides a method for predicting the fragment hazard produced by the detonation of stacks of munitions (Figure 2). This is accomplished by using characteristic fragment data obtained from small-scale tests that are representative of larger stacks of munitions. Full trajectories are calculated for each fragment recovered in the small-scale tests, and calculations are made using the fragment trajectories to determine the hazard to a specified target. Calculation of fragment ricochet makes possible the accurate determination of hazard to three dimensional targets, since low angle fragments may skip through numerous hazard zones before coming to rest where they are collected (Figure 3).

FRAGHAZ runs under a MONTE CARLO or FULL FACTORIAL option, both of which handle the uncertainties associated with initial fragment elevation angle and velocity, fragment drag coefficients, heights of fragment trajectories, origin above the ground surface, soil ricochet, wind speed, and altitude of the ammunition stack site. For this study, FRAGHAZ was run using the MONTE CARLO option, with sixty replications (the recommended number) for each case. The wind speed was set to zero, the altitude of the stack site was selected as sea level, the inert stand-off of the stack was set to the pallet thickness (or height of truck plus pallet height), and the soil constant for ricochet was allowed to vary over a range that covered different types of soils. The statistical output of the program used in this study was in the form of fragment densities and probabilities of target hits.

Fragmentation data for inclusion into the FRAGHAZ program has been collected for a number of fragmenting munitions, including MK-82 GP bombs and 155mm projectiles. The general consensus in the explosive safety community is that, for this study, a representative "worst case" munition is the Comp B-filled M107 155mm projectile, because of the fragment hazard and the large stocks of this munition maintained by the Army. The explosive weight of an M107 is 7.0 kg (15.4 lbs).

DAMAGE CRITERIA

Since this study is concerned with temporary encampments, the main concern is with hazards to personnel, rather than damage to permanent buildings. In the past, the U.S. Dept. of Defense Explosive Safety Board (DDESB) has specified the following hazard criteria for personnel:

a. Fragment impact kinetic energy of at least 79 joules (58 ft-lb).
b. Areal density of at least one hazardous fragment per 56 m^2 (600 ft^2).

The areal density criterion is approximately equivalent to a hit probability of 0.01 for a standing man (target area considered to be 0.58 m^2 (6.2 ft^2)).

Recently, however, the DDESB has considered skin penetration as a more accurate injury criterion, and

this has been incorporated into the FRAGHAZ program (McClesky 1992). A number of FRAGHAZ runs were made during this study using both the 79-joule and the skin-penetration criteria. A comparison of the two criteria showed that for all practical purposes, there is no difference between calculations made using the skin penetration criteria and those using the 79-joule criteria.

An additional hazard measure provided by FRAGHAZ, called a percentile value, is used in calculating hazard density and probability of a hit. Since the FRAGHAZ program calculates output data for a number of simulations, this value may be thought of as a confidence level. If we use the 90-percentile value given in Table 2, for example, we can be 90 percent confident that the hazard densities and probability of a hit will not exceed this set of values.

STORAGE METHODS

The fact that this analysis is concerned only with field storage limits the number of ammo storage methods that need to be considered. The storage methods that would most likely be used at a temporary field site are uploaded trucks or ammo stacked on the ground surface. At the recommendation of the U.S. Army Technical Explosive Safety Center, the Palletized Load System (PLS) was considered as the method of storage. Several possible PLS configurations are shown in Figure 4.

MODELING CONSIDERATIONS

Although there are numerous variables to be considered in modeling the fragment hazard from the detonation of one or more ammunitions stacks, in many cases the problem can be simplified by making a few logical assumptions. These assumptions are made possible because of the fact that our ultimate goal is to establish a <u>relative</u> index of risk associated with QD violations, rather than the <u>actual</u> probability that an effect will occur.

The fact that we are considering the PLS as the basic ammunition load imposes a minimum explosion size for this analysis. Whether the load is on a truck or off-loaded on the ground, it can be considered as a single ammunition stack. Any adjacent stacks should be separated enough that, even if one stack is sympathetically detonated by an adjacent one, each stack explosion can be considered as an independent event and accounted for by the formula given in above. However, since it is impossible to predict how the ammo stacks will be arranged in the field, stacks consisting of multiple PLS loads are also considered.

EFFECTS OF STACK GEOMETRY

Since the PLS load may either be on a truck or sitting on the ground, calculations were run for different standoff heights above the ground to determine the probability of hit to a standing man. Another factor that could possibly influence the hazard level is the geometric configuration of the ammo stack; i.e., whether the ammo pallets are strung out along the ground, or stacked in tiers several pallets high. These possibile stack variations are illustrated in Figure 5. Since experimental data indicates that essentially all hazardous fragments originate from projectiles on the face of the stack (McClesky, 1988), the three different stack configurations were each run with the same number of projectiles on the stack face. The calculations indicate that any variations in fragment hit probabilities due to stack standoff height or stack geometry are not significant (especially since we are only concerned with a relative risk factor). This leaves one important factor of interest for defining the fragment hazard - the NEQ, or, for FRAGHAZ calculations, number of projectiles on the face of the stack.

NET EXPLOSIVE QUANTITY (NEQ)

Although the fragment hazard is a direct function of the number of projectiles on the face of the stack, it can also be directly associated with an NEQ. Because of the fact that the stacks are comprised of PLS loads, which limits the depth of the ammunition stack. Referring to Figure 4, it can be seen that a PLS load is 10-12 projectiles deep (the width of the truck bed) and 28 projectiles in length. We also assume that several PLS loads may be stacked together - close enough to be considered as one stack. The probability of a fragment hit from several stack sizes was calculated and is plotted in Figure 6. Although Table 10-1 in Ref. 1 refers to maximum NEQ's of 4000 kg, larger stack sizes are shown in Figure 6. These curves are valid for open storage of ammunition and, although they are probably somewhat low for an uploaded truck, they should be sufficiently accurate for calculations of <u>relative</u> risk levels.

Curves 1 & 2 in Figure 6 are for PLS loads which combine projectiles and propellant, while the remaining curves are for projectiles only (Figure 4). The QD's at the FRAGHAZ-calculated one-percent probability level are compared with the current Theater of Operation QD's in Table 1. The QD's given in the current standards for TO's are also shown on Figure 6. These current QD distances are printed on the figure and point to the locations on the curve (ranges from the detonation point) where the the QD's occur. Note that the current TO QD's allow of hit probabilities of up to 20 percent.

Table 1 Comparison of Theater-Of-Operation Quantity-Distances in Current Standards with Those Calculated by FRAGHAZ			
		FRAGHAZ Calculations	
Net Explosive Weight (NEW) (kg)	QD from Current Standards[1] (m)	Risk Level[2] for QD of Current Standard (%)	QD for 1% Risk Level[2] (m)
700	180	6.3	410
1401	180	13.0	510
2452	185	22.0	570
4904	260	21.4	650
9809	360	19.5	780
19618	510	13.2	830
39235	720	5.1	850

[1] Chapter 10 of DOD 6055.9-STD
[2] Risk level indicates probability (in %) of a hazardous fragment hit to a standing man.

Table 1 Comparison of Theater-Of-Operation Quantity-Distances in Current Standards with Those Calculated by FRAGHAZ

FACTORS OF INCREASED RISK FROM FRAGMENT HAZARDS

The purpose of this study was to determine the relative increases in risk that results from reducing the separation distances, between an ammo storage point and a target of interest, below the QD guidelines currently stated in the DDESB Standards. However, if we refer to relative increases, the question arises, "relative to what?" It is assumed that the current guidelines are the QD values given in Column D4 of Table 10-1 of the DDESB standards, which apply to public traffic routes and inhabited buildings or troops in tents in a theatre of operations. The QD values in Table 10-1 apparently are taken from the current NATO manual (Table 4-1), but there is no clear statement as to the criterion upon which the values were based, such as one lethal fragment-per-56m^2.

In view of this predicament, two different approaches were taken in this analysis to evaluate the increase in risk. The first was to establish a new QD based on a criterion of a one-percent probability of a lethal fragment hit against a standing man (or woman). Their value, called QD_1, was established solely from the FRAGHAZ calculations. The second approach is based on the QD values given in Column D4 of Table 10-1 of the DDESB standards (called QD_s, here), but with an initial risk factor assigned to QD_s that is also defined by the FRAGHAZ calculations. The following discussion describes the increases in risk based on these two points of reference.

The initial examination of the increase in risk is based entirely on the FRAGHAZ output, presented in Figure 6. The QD_1 value for each curve is defined as the distance at which there is a one-percent probability of a hit against a standing man. Using this information, the curves in Figure 6 can be displayed as factors of increased risk vs. percent reduction in QD. The risk factors are derived by dividing the probability-of-hit value at some Range R, that represents a reduced QD, by the probability of a hit at QD_1. The associated percent reduction in range is found by dividing range by the value of QD_1 and subtracting the result from 1.0, then multiplying by 100, as shown in (3).

$$\% \text{ reduction} = ((1 - R/QD) * 100) \qquad (3)$$

By performing the above conversions, we arrive at the curves shown in Figure 7. The shapes of these curves look very similar those shown in Figure 6, except that they are mirrored on the X-axis.

To determine the increased risk for a given distance, the next highest NEQ (for the ammo stack of interest) is selected from the curves of Figure 7. The value of QD_1 can be read from Figure 6. Using these values, Eq. (3) can be solved to find the percent reduction in QD. By locating the resulting value on the X axis of Figure 7 (or Figure 8), a vertical line can be drawn to intersect the appropriate curve for the given NEQ. A horizontal line drawn from the intersection point across to the Y axis gives the increase in risk incurred by violating QD_1.

RISK FACTORS USING QD's PRESCRIBED FOR TO's

The QD's officially prescribed for Theatres of Operation by the DDESB standards are given in Table 10-1 of DOD 6055.9-STD. The values given in Column DR of Table 10-1, for public traffic route distances, are assumed to apply for this analysis, and are designated here as values of QDs.

To transform the FRAGHAZ calculations into a family of curves reflecting these official values of QD_s, the probability of a hit for each point on the curves of Figure 6 is divided by the probability of a hit for QD_s particular charge weight. The percent reduction in QD values associated with each transformed point were again determined by Eq. 3. Notice that these new curves, shown in Figure 9,

are somewhat different from the curves shown in Figure 7. The curves are not numbered in a visual order, as are those using the 1% criteria (that is; stacked from lower to higher NEQ's). The reason for the seemingly random reordering of the curves can be found in Table 3, but is more readily observed in Figure 6. The probability-of-hit values for the QD_s (from the DDESB standards) are not monotonic, so the conversion from probability to a risk factor reorders the curves vertically on the page, as seen in Figure 9. Note also, that all curves converge to a risk factor of one (as they should), for a zero percent reduction in QD_s. As with figure 7, the lower portion of Figure 9 is enlarged, smoothed, and replotted in Figure 10.

The increase in risk may again be determined as above. As an example, assume that we have an NEQ of 4,000 kg at a distance of 208 m from a target of interest (e.g., a mess tent). From Figure 9, we see that the next highest value is 4,904 kg, for Curve No. 4. Looking back at Figure 6 (or Table 3), we see that the recommended QD for TO's is 260 m. Substituting in Eq. 1, the percent reduction from the recommended value of QD_s is = ((1 - 208/260) * 100), or 20 percent. Using Figure 10 (because, at the range of interest, it is easier to read than Figure 9), a vertical line is drawn-from 20 percent on the ordinate scale to intersect curve 4, then read across horizontally to find a risk factor of approximately 1.5. This means that a hit by a hazardous fragment at a distance of 208m is 1.5 times more likely than at the recommended QD_s value of 260m. This may not sound like a large increase, but from Figure 6, it can be seen that even at the prescribed value of QD_s, the probability of hit by a hazardous fragment is approximately 21 percent. Thus, we have increased our probability of a hit from 21 percent to approximately 30 percent. As a check, we can look back at Curve 4 in Figure 6 and see that the probability of hit by a hazardous fragment at 208m is, indeed, approximately 30 percent.

FRAGMENT HAZARD FROM MULTIPLE DETONATIONS

The fragment hazard resulting from detonations of multiple ammo stacks can be established by determining the risk associated with each single ammo stack, and applying Equations 1 or 2. Since we are unable to determine the conditional probability of a second ammo stack exploding, given that an adjacent stack initially explodes, we must make certain assumptions. To be conservative, it is assumed that, if the ammunition stacks are not separated by a barricade or by a distance less than the prescribed QD, the total NEQ of the multiple stacks can be considered as a single event. If the stacks <u>are</u> properly separated, it is assumed that if one stack explodes, the other will not (at least not within a close time interval, since the main danger will be a cook-off of the secondary stacks due to fires created by burning debris). Given these assumptions made, the fragment hazard probabilities can be taken directly from Figure 6 or increase in risk from Figures 7-10.

SYMPATHETIC DETONATIONS

Determining the probability of sympathetic detonation of a second ammo stack by the explosion of a nearby stack presents a much more difficult problem. As with the selection of a "worst case" <u>donor</u> munition (the 155 mm projectile used in this study), there has been much discussion about selection of a "worst case" <u>acceptor</u> munition (i.e., one that is most succeptable to detonation by a fragment impact). Unfortunately, the most probable candidate is considered too dangerous to test, and without sufficient data many assumptions are necessary to investigate this portion of the problem. It appears that the main factors affecting the probability of a detonation due to a fragment impact are the fragment mass and impact velocity. However, many other factors - e.g., fragment shape, impact angle, fragment temperature, whether the fragment penetrates the target or not - all contribute to the possibility of causing a detonation.

While the FRAGHAZ program can predict the probability that a fragment with a certain kinetic energy

will hit a given target at a given distance from an explosion, we do not have the information that is necessary to determine the energy required to cause a detonation by an impact. Figure 11 shows the probability of a target (in this case a PLS ammo stack) being hit by fragments of a range of energy levels (as calculated by FRAGHAZ). Curve 1 shows the probability of a hit vs. distance for all fragments. Curve 2 shows the probability of a hit by a fragment with a kinetic energy of 1500 joules (1100 ft-lbs) or greater, and Curve 3 shows fragments with a kinetic energy of 7450 joules (5500 ft-lbs) or greater. Notice that the calculations show that the larger, high-energy fragments are only encountered at the closer ranges. Curve 4 shows the effects of a barricade on the probability of a hit for all fragments, indicating that a barricade can be very effective in reducing the risk of sympathetic detonations of adjacent stacks. This is backed up by the results of the Trench Storage Tests (Davis et al., 1992), which demostrated that a barricade beween two uploaded ammo trucks can prevent the sympathetic detonation of one truck by the detonation of another.

The fact that barricades can drastically reduce the risk to personnel and the possibility of sympathetic detonation of adjacent ammo stacks should always be kept in mind by field commanders. Although trench storage may not be suitable for all climates, terrains types, or situations, there are other possibilities. In some cases, it may be possible to take advantage of natural terrain features (such as the side of a hill). If time permits, barricades could possibly be constructed of barricades between ammo stacks. FRAGHAZ now includes provisions to account for the effect of various shapes and sizes of barricades, and calculational results shown in Figure 12 demonstrate how barricades can drastically minimize fragment hazard and/or sympathetic detonations when and uploaded ammo truck detonates. However, it must be pointed out that, although the usefulness of barricades in reducing fragment hazard is generally accepted by the explosive safety community, there is little data to back up the calculations.

SUMMARY

While limitated existing data dictated that this study would not be exaustive in scope, the results of this analysis provide a useful indication of the increased risk to personnel incurred by violating perscribed QD's in theatres of operation. Additional analyses, along with verification by experimental data, should lead to comprehensive guidelines that may be incorporated in future revisions of DOD standards. Meanwhile, it is hoped that the results of this analysis will be translated to a computerized format that will provide the field commnader with easy to use, usefull decision aid.

ACKNOWLEDGEMENTS

The analysis presented herein was performed by the U.S. Army Engineer Waterways Experiment Station. We gratefully acknowledge permission from the Chief of Engineers to publish this pager.

Also, the author would like to thank Mr. Michael Swisdak, Naval Surface Warfare Center, and Mr. Frank McClesky, Booz-Allen and Hamilton, Inc., for assistance with the FRAGHAZ calculations and modifications to the program that made this study possible.

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Figure 1. Problem Definition.

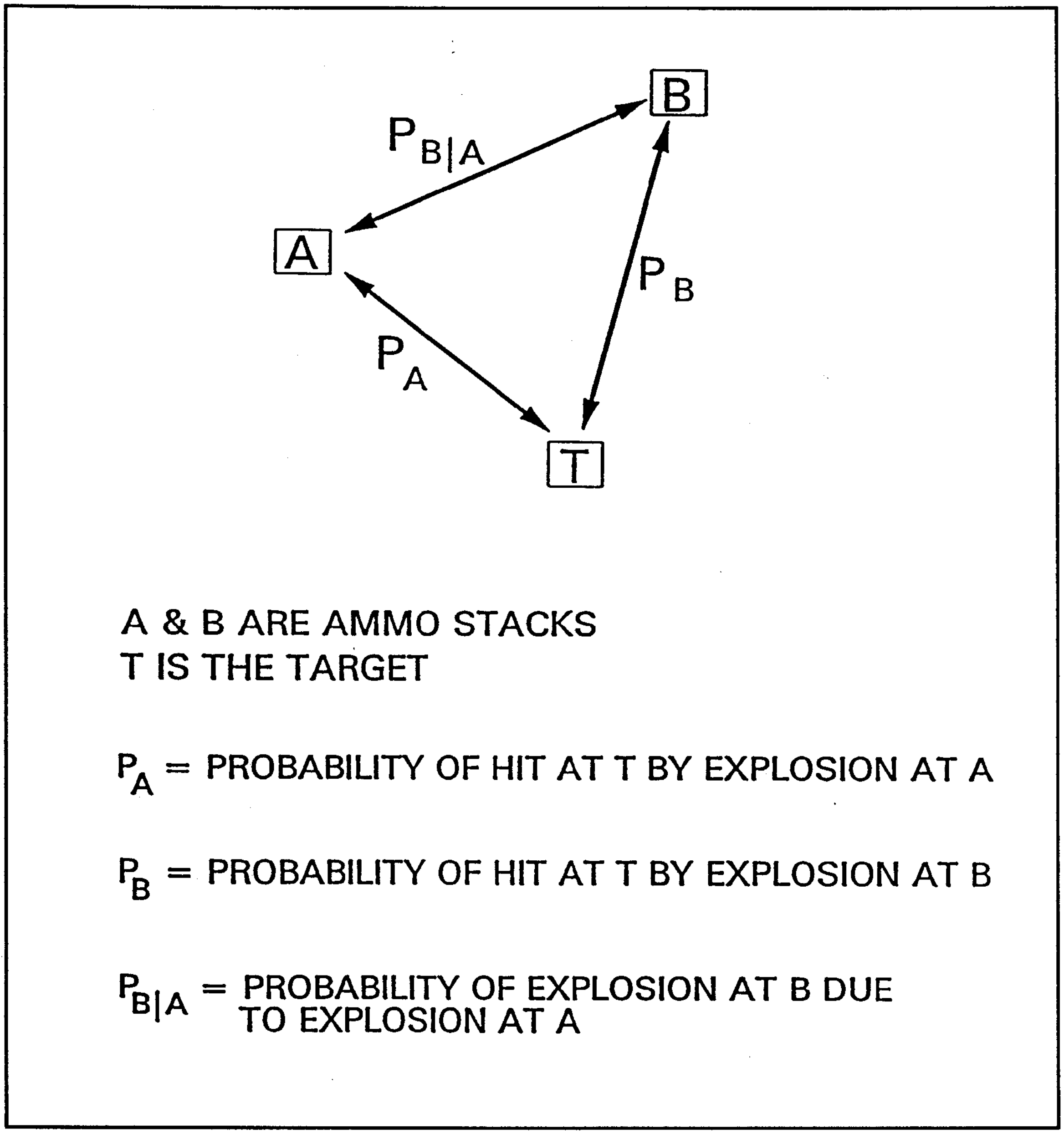

Figure 1. Problem Definition.

Figure 2. Stack Fragmentation Simuation.

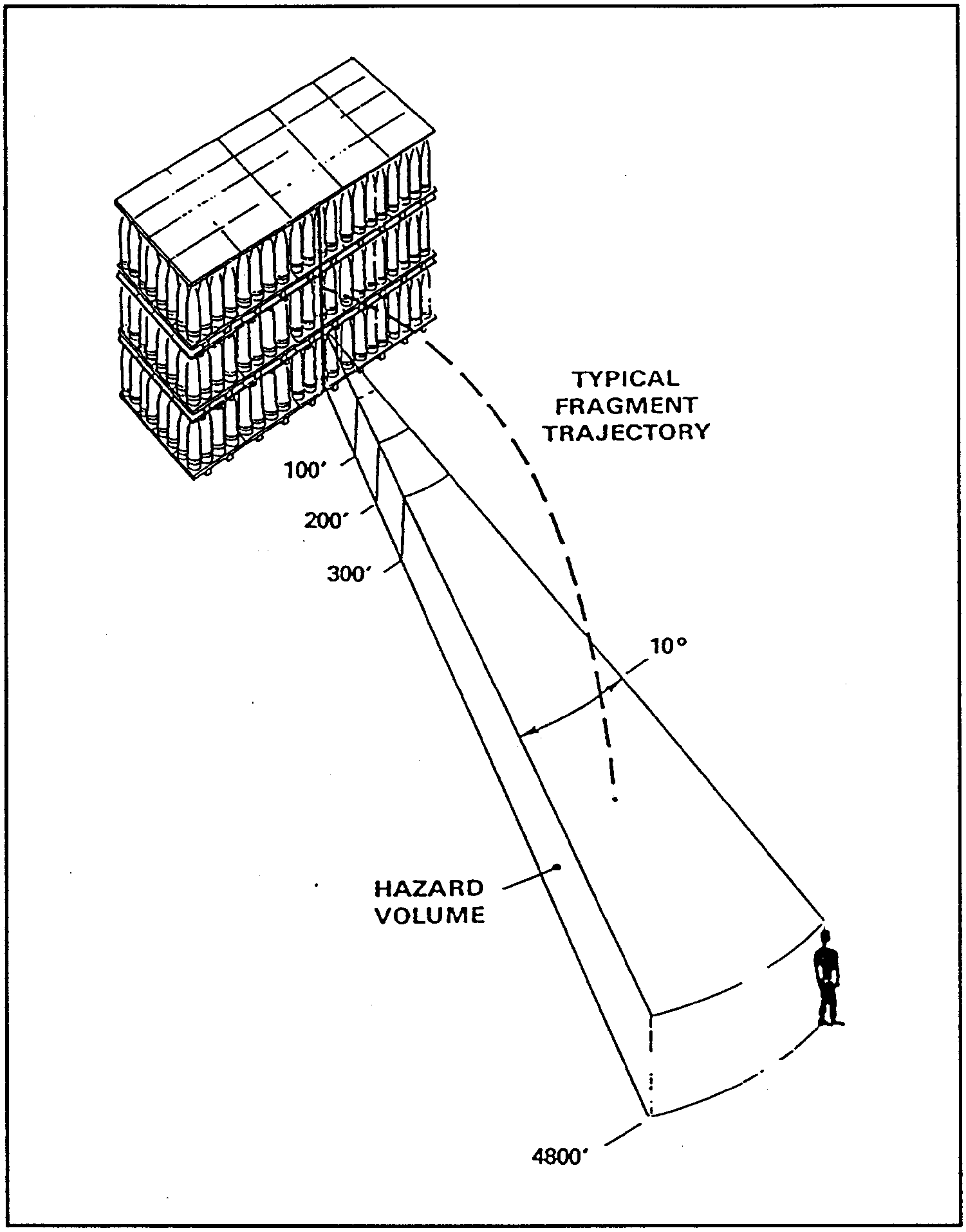

Figure 2. Stack Fragmentation Simulation.

Figure 3.
Illustration of how ricochet causes fragments to pass through sample areas.

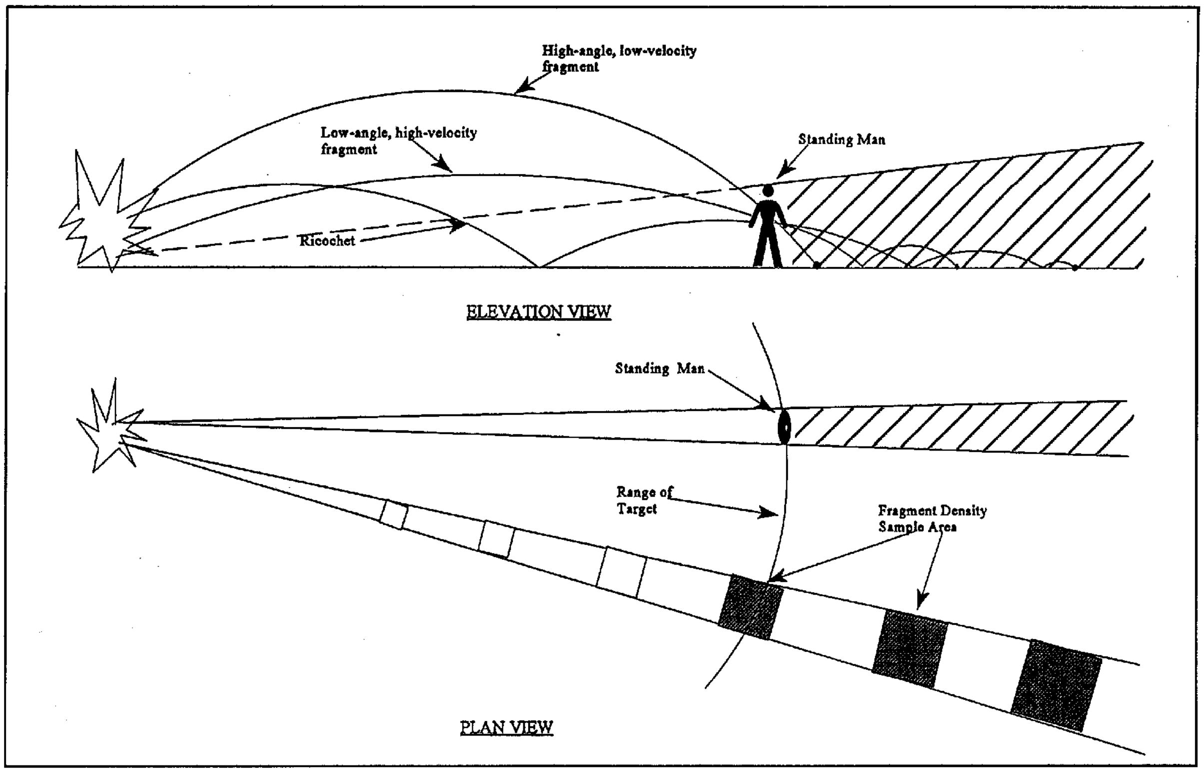

Figure 3. Illustration of how ricochet causes fragments to pass through multiple sample areas.

Figure 4. Possible palletized Loading System (PLS) loading configuration for 155-mm projectiles.

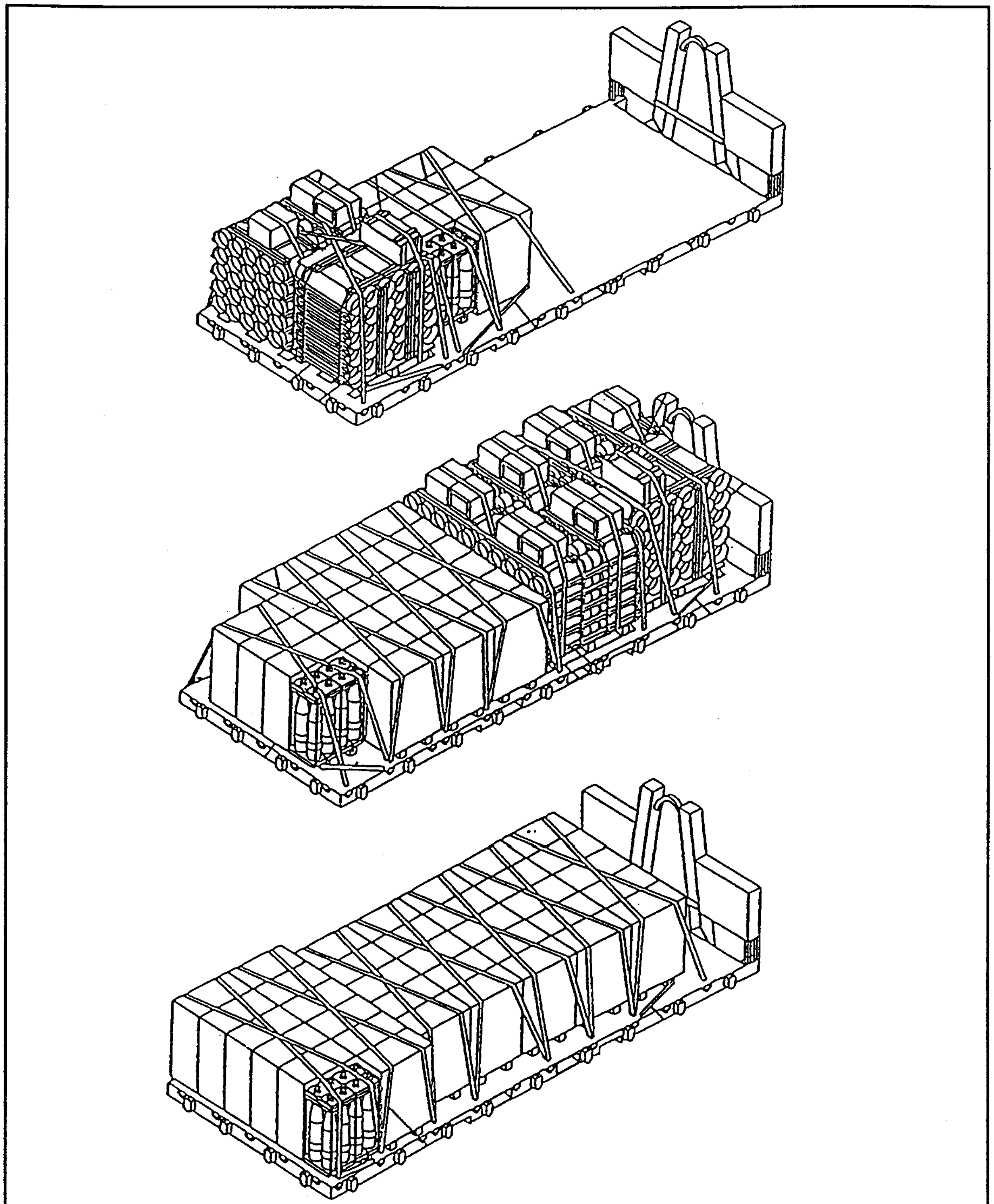

Figure 4. Possible Palletized Loading System (PLS) loading configuration for 155-mm projectiles.

Figure 5. Stack Geometry.

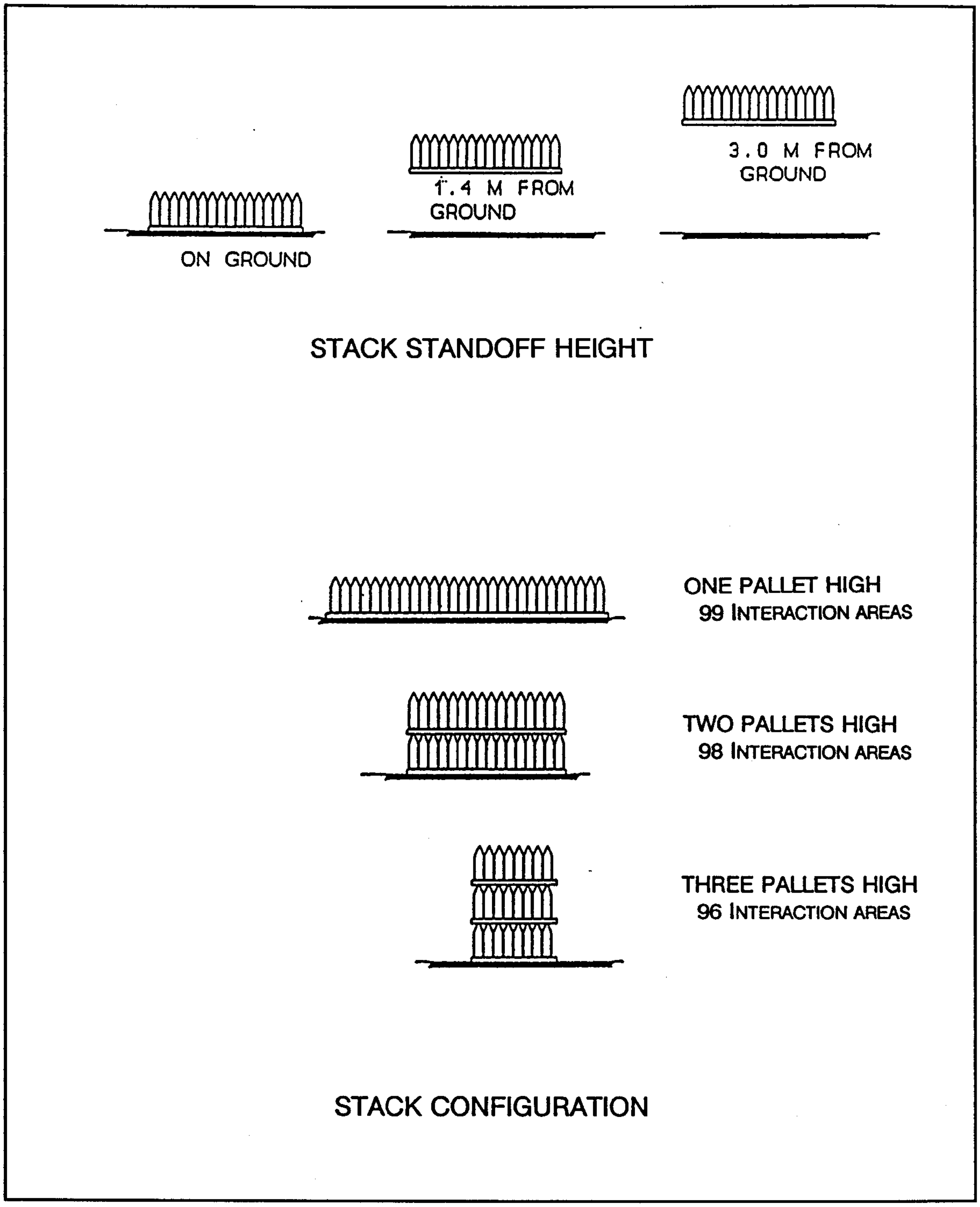

Figure 5. Stack Geometry.

Figure 6. Probability of hit for several Net Explosive Quantities, as determined by FRAGHAZ calculations. The numbers with arrows are the Q-D's specified in the current DDESB standards for TO's for the corresponding NEQ's.

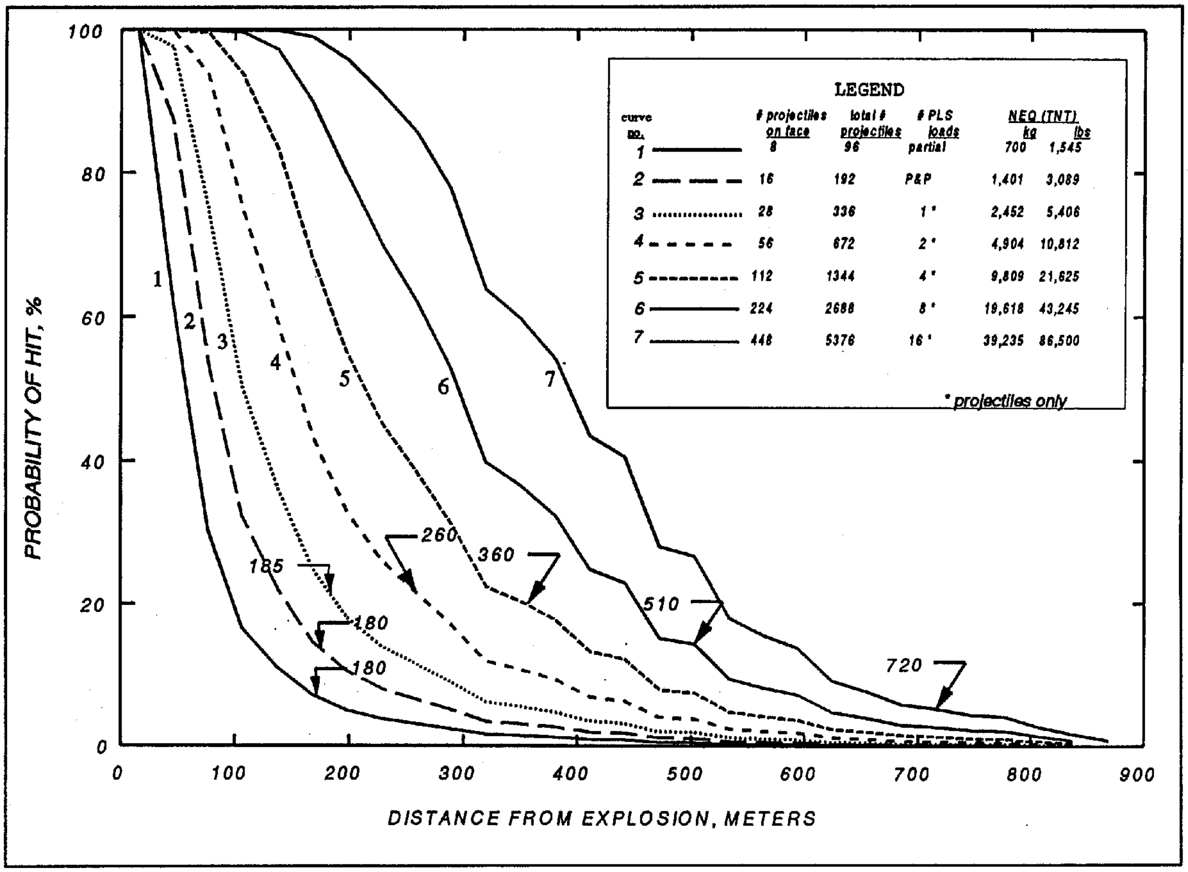

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Figure 7. Increases in risk due to reduction in QD's calculated from 1% hit probability distance.

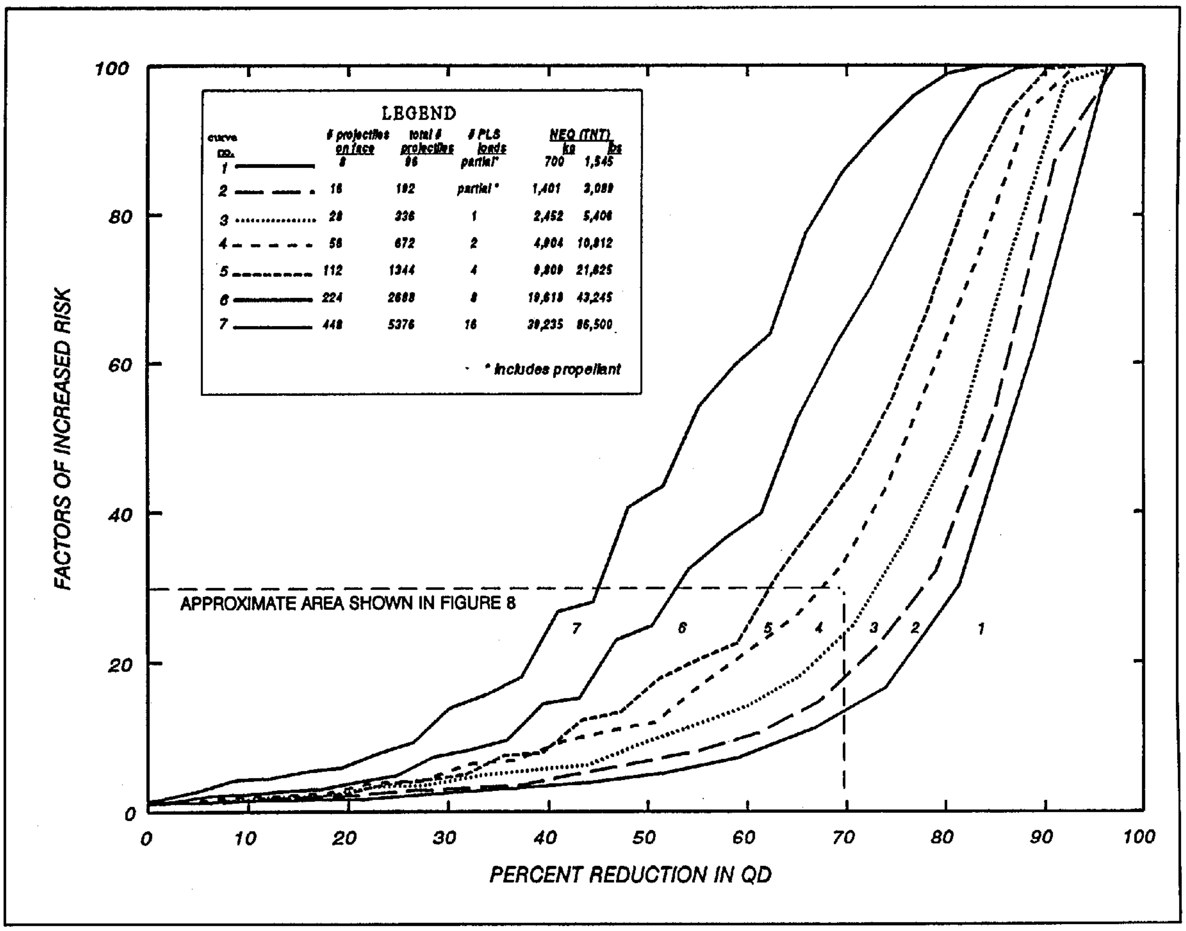

Figure 7. Increase in risk due to reduction in QD's calculated from 1% hit probability distance.

Figure 8. Increases in risk due to reduction in QD's calculated from 1% hit probability distance (from Figure 7, enlarged and smoothed).

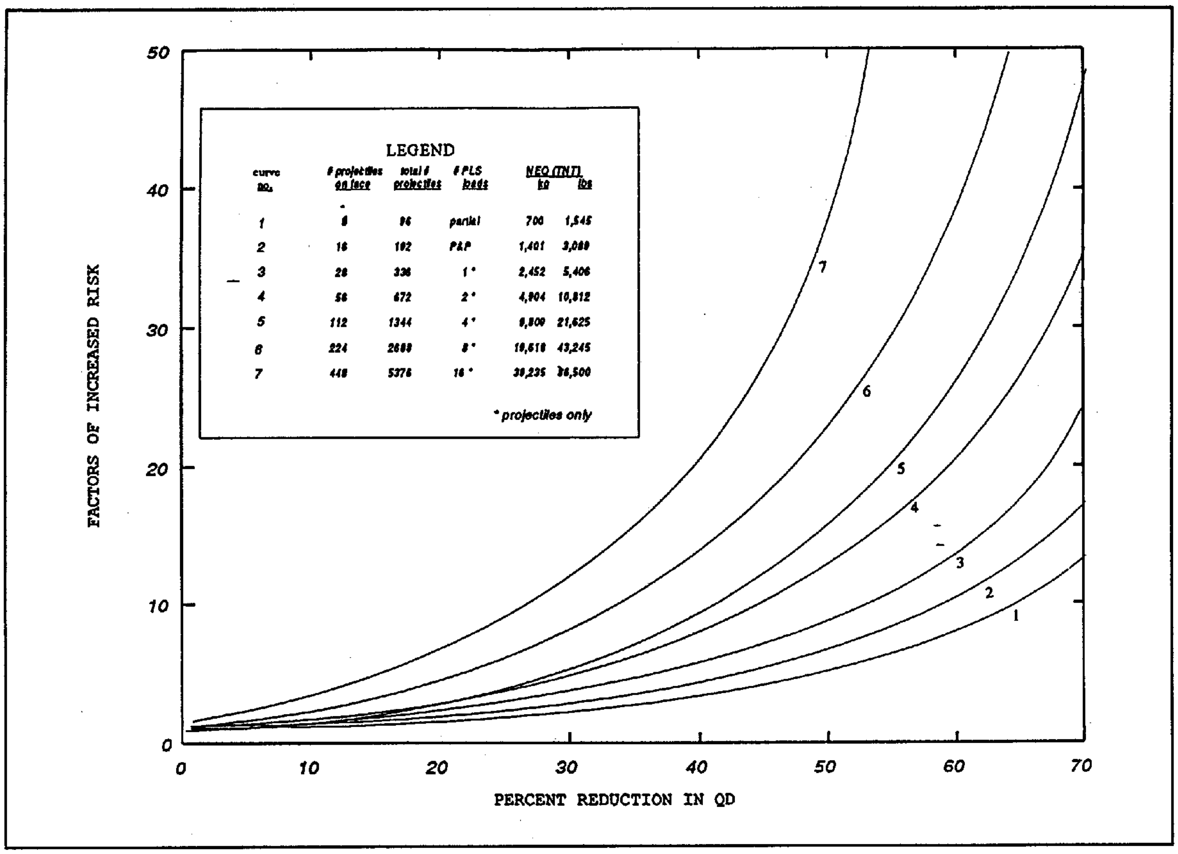

Figure 8. Increase in risk due to reduction in QD's calculated from 1% hit probability distance (from Figure 7, enlarged and smoothed).

Figure 9. Factors of increased risk vs. percent reduction in QD for Theaters-of-Operation.

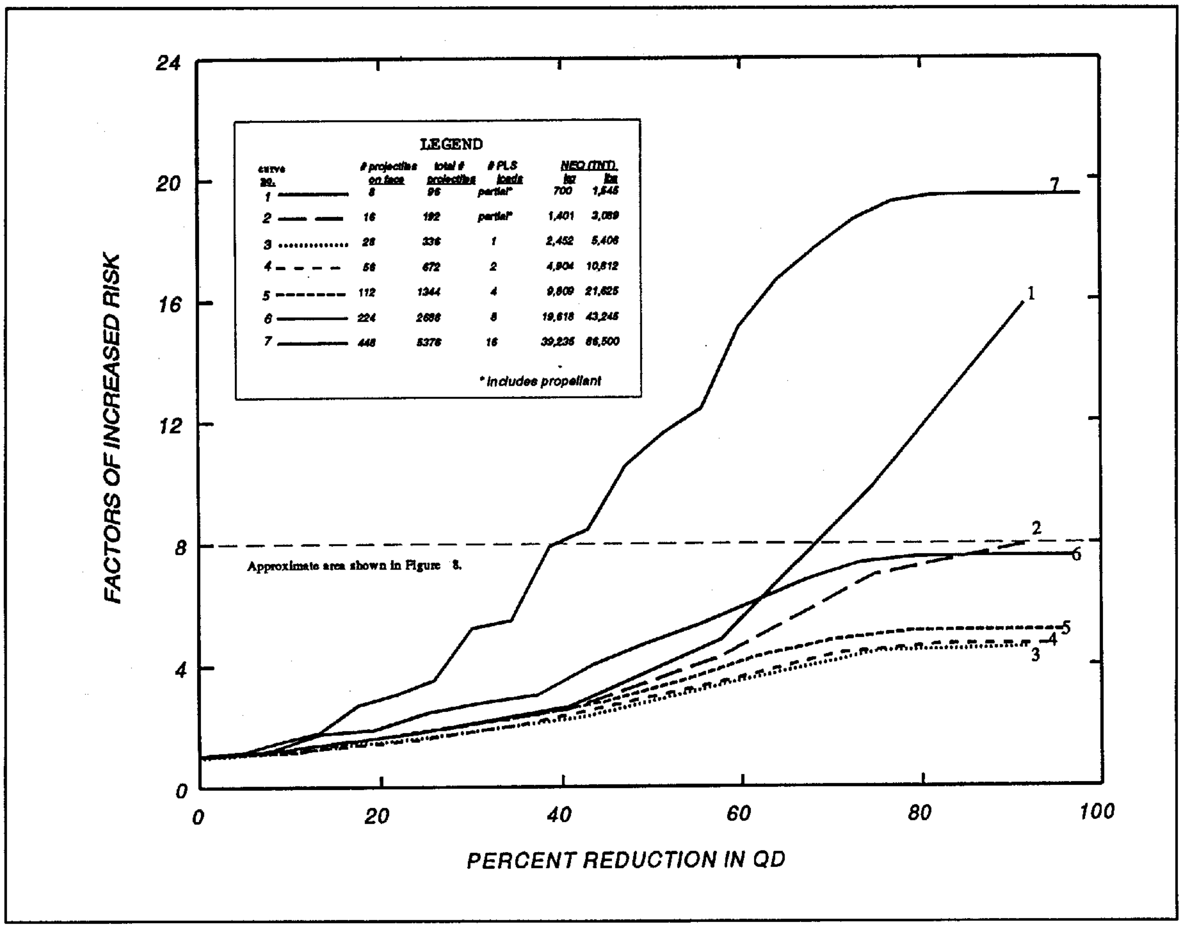

Figure 9. Factors of increased risk vs. percent reduction in QD for Theaters-of-Operation.

Figure 10. Factors of increased risk vs. Percent reduction in Theater-of-Operation QD's (enlarged from Figure 9).

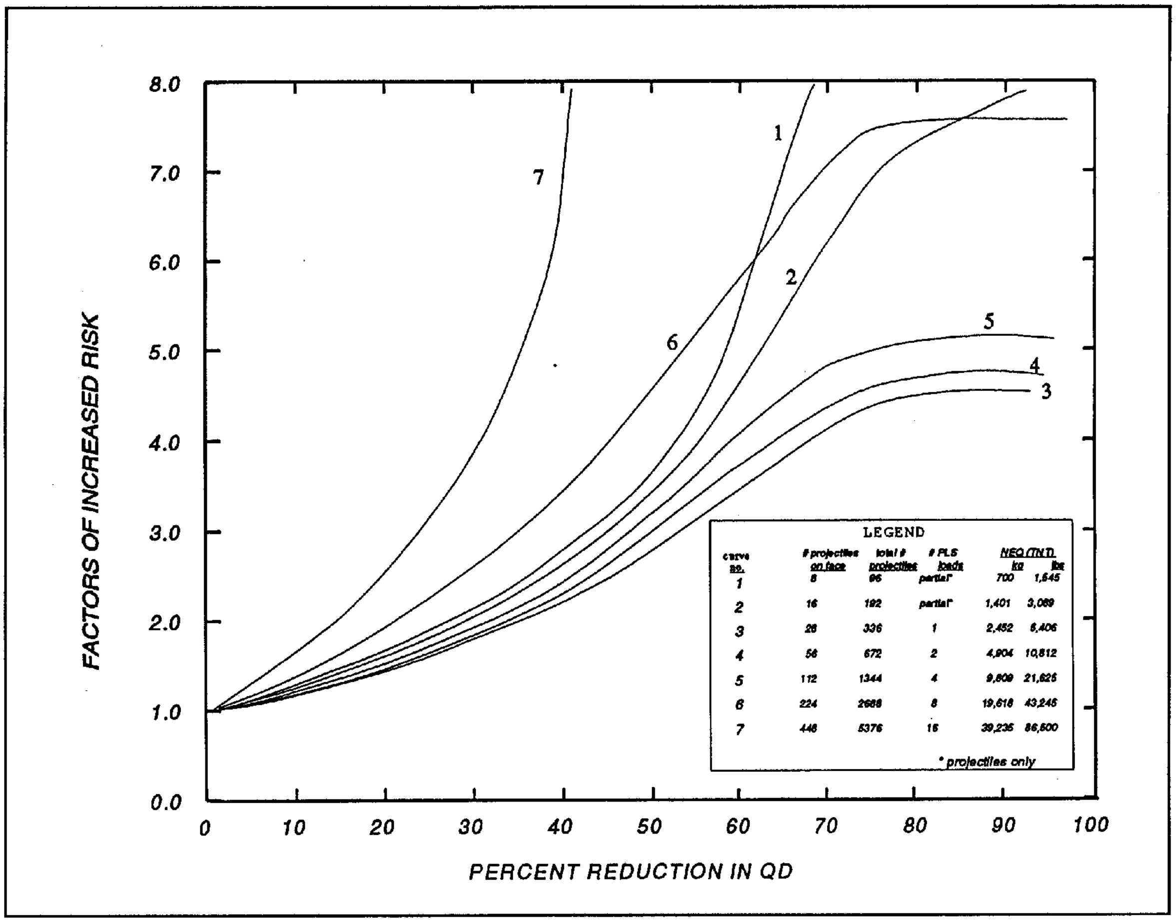

Figure 10. Factors of increased risk vs. percent reduction in Theater-of-Operation QD's (enlarged from Figure 9).

Figure 11. Probability of fragments hitting ammo stack.

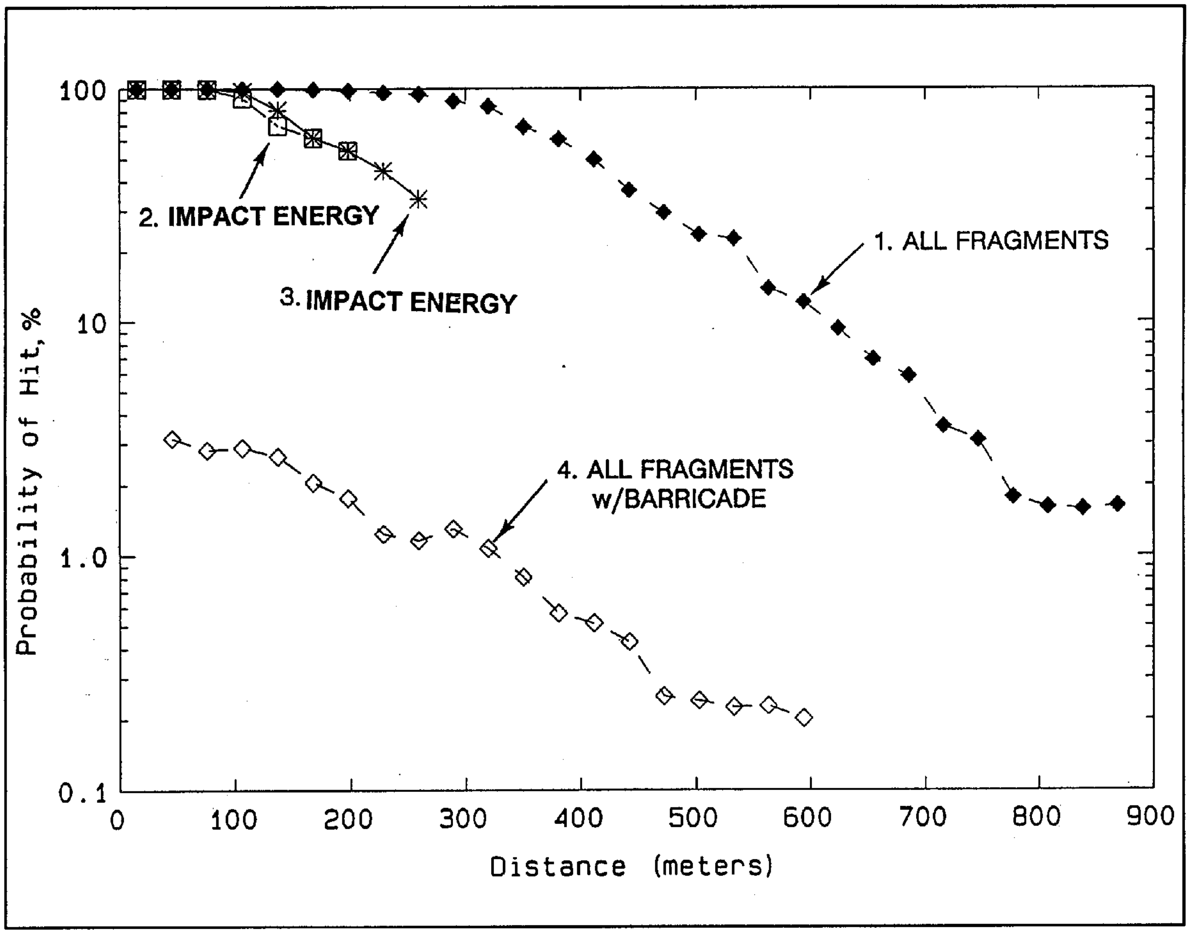

Figure 11. Probability of fragments hitting ammo stack.

Figure 12. Effect of barricades on hazard to standing man (ammo truck detonation).

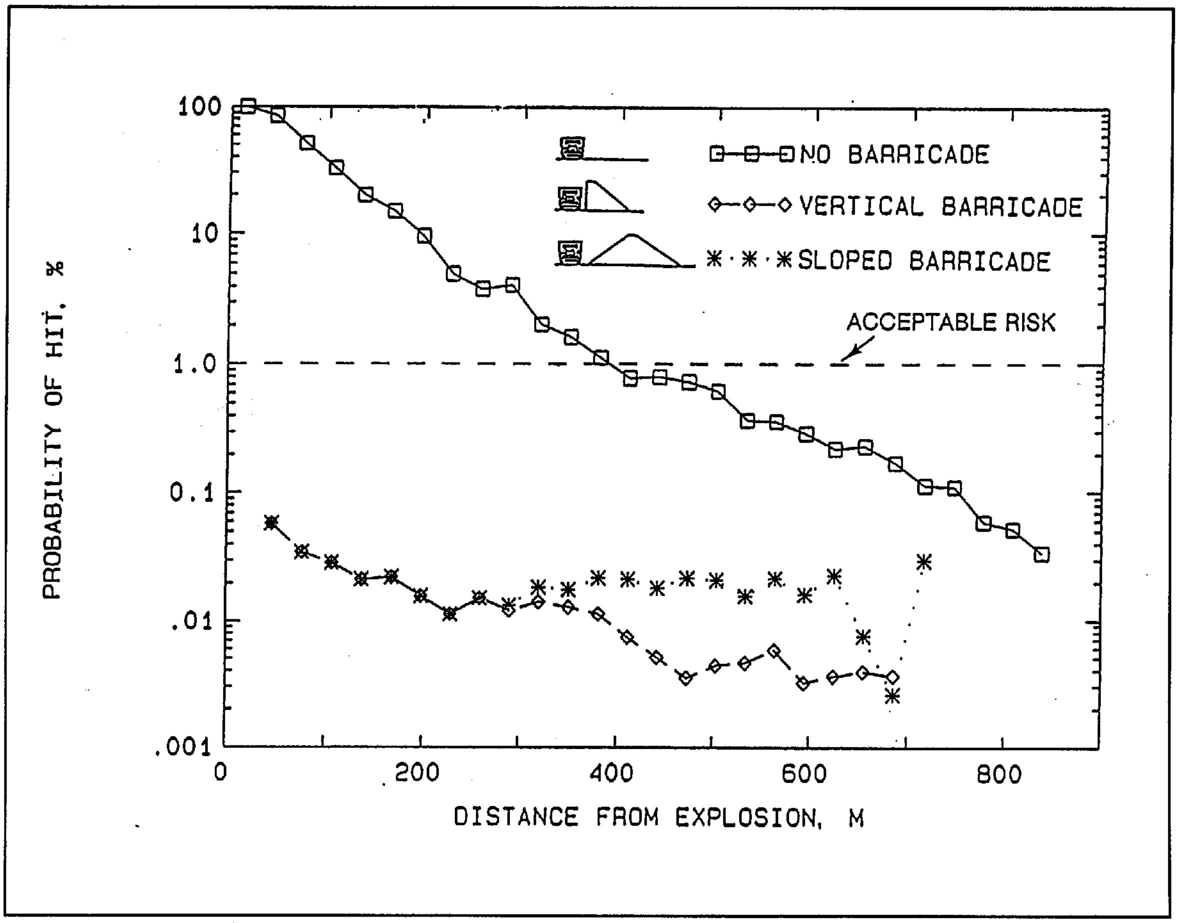

Figure 12. Effect of barricades on hazard to standing man (ammo truck detonation).